

Utah State University

**DigitalCommons@USU**

---

Reports of Center Studies

Research

---

2009

## Formulating a Conceptual Base for Secondary Level Engineering: A Review and Synthesis

Rodney L. Custer

Jenny L. Daugherty

Joseph P. Meyer

Follow this and additional works at: [https://digitalcommons.usu.edu/ncete\\_cstudies](https://digitalcommons.usu.edu/ncete_cstudies)



Part of the [Engineering Commons](#)

---

### Recommended Citation

Custer, R. L., Daugherty, J., & Meyer, J. (2009). Formulating the conceptual base for secondary level engineering education: A review and synthesis.

This Report is brought to you for free and open access by the Research at DigitalCommons@USU. It has been accepted for inclusion in Reports of Center Studies by an authorized administrator of DigitalCommons@USU. For more information, please contact [digitalcommons@usu.edu](mailto:digitalcommons@usu.edu).





# **Research In Engineering and Technology Education**



**ncete**™

**NATIONAL CENTER FOR ENGINEERING  
AND TECHNOLOGY EDUCATION**



This material is based on work supported by the National  
Science Foundation Under Grant No. ESI-0426421

## **Formulating a Concept Base for Secondary Level Engineering: A Review and Synthesis**

Rodney L. Custer, Jenny L. Daugherty, Joseph P. Meyer

### **Introduction**

In recent years, there has been a growing interest in science, technology, engineering, and mathematics (STEM) education across the K-16 spectrum. While much of this interest has concentrated on science and mathematics, technology and engineering are emerging as authentic educational problem solving contexts, as well as disciplines in their own right at the K-12 level. Over the past 20 years, the technology education field has concentrated on defining and implementing a set of content standards, the *Standards for Technological Literacy* (ITEA, 2000) (STL), with mixed results. On a national scale, the field continues to evolve from its historical industrial arts base toward more contemporary approaches to curriculum and pedagogy. In spite of the STL, which were designed to define the content base for technology education, practice continues to be driven by projects and activities with little focus on specific student learning outcomes. In addition, over the past decade, the field has shifted toward an interest in an alignment with engineering.

Corresponding with technology education's shift in emphasis has been the engineering profession's emerging interest in K-12 education. A significant part of this emphasis can be attributed to a concern among engineering educators that insufficient numbers of students, including women and minorities, are being attracted into and prepared for post-secondary engineering education. More positively, there is a growing awareness that a well crafted engineering presence within the K-12 curriculum provides a rich and authentic contextual base for mathematics and science concepts. Engineering-oriented programs, particularly at the secondary level, range from those designed to promote general engineering/technological literacy (designed for all students) to those designed to prepare students for post-secondary engineering education.

A larger scale initiative focused on pre-college engineering is the National Center for Engineering and Technology Education (NCETE). NCETE was funded in 2004 through the National Science Foundations' (NSF) Centers for Learning and Teaching program. Over the past five years, the nine university consortium has engaged in a variety of activities including teacher professional development, the preparation of doctoral students, and research. Over the past year, the activities of the Center have shifted more directly to a focus on research. One key problem that has emerged from the work of the Center has been the lack of a well defined and articulated body of content for K-12 engineering. This void poses serious problems for curriculum and professional development, as well as for research. Specifically, high quality curriculum materials should be based on a well defined set of concepts. In the absence of this conceptual base, materials tend to feature sets of engaging activities, lacking a focus on conceptual learning as well as the rigor necessary for accountability. The same problem occurs with professional development and pre-service teacher education. High quality teacher preparation and development require congruence with a well-defined base of content and concepts.

The development of meaningful learning, teaching, and assessment is exceptionally problematic in the absence of a clear understanding of the conceptual base appropriate for K-12 engineering. This study is designed to address this void. Fortunately, the interest in K-12 engineering over the past decade has yielded a variety of activities, projects, and products that

can inform the process. Among these are the development of various science, technology, engineering, and mathematics (STEM) standards, engineering-oriented curriculum, studies at the National Academy of Engineering, and research designed to understand engineering outcomes appropriate for K-12 students. Given this work and the need for a well defined conceptual base as a foundation for curriculum, professional development, and research, a study designed to coalesce engineering concepts for the secondary level is necessary.

### **Purpose of the Study**

The purpose of the study was to identify and refine a conceptual foundation for secondary school engineering education. Specifically, this study sought to address the following research questions:

1. What engineering concepts are present in literature related to the nature and philosophy of engineering?
2. What engineering concepts are embedded in secondary level science, technology, engineering, and mathematics standards?
3. What engineering concepts are embedded in secondary level engineering-oriented curriculum?
4. What engineering concepts have been identified in the related research literature?
5. What engineering concepts are deemed core for secondary level education by practicing engineers and engineering educators?

Key input activities included conducting a review and synthesis of extant educational materials focused primarily on standards, curriculum materials, and various research studies. In addition to these materials, literature from the history and philosophy of engineering was also reviewed and included in the analysis. Also included in the process was a series of focus groups sessions conducted with selected engineering educators and practicing engineers to identify and classify their recommendations of concepts appropriate for secondary level engineering. As a final phase of the process, a reaction panel of engineering and technology education experts was convened.

### **Literature Review**

Numerous reasons have been articulated for the inclusion of engineering into K-12 education. Erikson and Custer (2008) concisely summarized three reasons including that engineering would help to (a) facilitate technological literacy, (b) provide a math and science learning context, and (c) enhance an engineering pathway. These reasons have spurred the growth of engineering at the K-12 level. For example, a 2007 NSF report reviewing engineering education identified numerous K-12 engineering programs including projects at Worcester Polytechnic Institute and the University of Colorado at Boulder; curricular programs such as *The Infinity Project* and *Project Lead the Way*; business-oriented programs such as the Ford Partnership for Advanced Students; and competitions such as the For Inspiration and Recognition of Science and Technology's Robotics Competition. Based on their review of K-12 programs, the authors of the report concluded that there are "many faces of engineering K-12 curriculum" (Aung, Kwasiborksi, & Soyster, 2007, p. 27).

As educators look for avenues to integrate engineering into secondary level education, K-12 engineering content must be defined. Many within technology education have targeted the engineering design process as the avenue for integration (Lewis, 2005; Wicklein, 2006). The

discourse about the implementation of engineering design into technology education has largely centered on process or “problem solving and the application of scientific understanding to a given task” (Hill & Anning, 2001, p. 118). Many instructors have taught engineering design problem solving by implementing a prescriptive, step-by-step approach, typically through a design process model. The prescriptive approach to teaching design however has been increasingly criticized because it contradicts both expert and novice designers’ approaches to the problem solving and design process (Lewis, Petrina, & Hill, 1998; Mawson, 2003; Welch, 1999; Williams, 2000).

Due to the evidence of the role of conceptual knowledge in expert design cognition, the lack of a defined content base and a primary focus on the procedural knowledge in K-12 engineering education is a concern. As has been thoroughly discussed in mathematics, a focus on process may not lead to conceptual learning (Eisenhart, Borko, Underhill, Brown, Jones, & Agard, 1993; Rittle-Johnson, & Alibali, 1999; Rittle-Johnson, Siegler, & Alibali, 2001). For example, Antony (1996) argued that teachers “may be lulled into a false sense of security by providing students with numerous investigations, open-ended problem-solving experiences, and hands on activities with the expectations that students are successfully constructing knowledge from these experiences” (p. 351). This need for conceptual learning calls into question educational programs that try “to focus on procedural knowledge such as problem solving or design, while assuming that the domain and context within which this takes place are either irrelevant or at best secondary” (McCormick, 1997, p. 149).

In addition, within teacher professional development effectiveness is seen to hinge on a defined content base. As Guskey (2003) stated, enabling “teachers to understand more deeply the content they teach and the ways students learn that content appears to be a vital dimension of effective professional development” (p. 749). Desimone, Porter, Garet, Yoon, and Birman (2002) agreed, arguing that high quality professional development must include “a focus on content and how students learn content; in-depth” (, p. 82). Similarly, Supovitz and Turner (2000) outlined components of high quality science education professional development and concluded that focus on subject-matter knowledge and deepening teachers’ content skills was critical. Specific to engineering professional development, one key finding of Daugherty’s (2008) study on secondary level, engineering-focused professional development is that the content dimension was either ill-defined or largely missing across the cases. The primary focus was on the process dimensions of engineering rather on engineering content or concepts.

### *Content and Conceptual Learning*

Learning can be defined as the social construction of knowledge. Individuals construct schemata or knowledge structures through experience and instruction. Schemata impact the learning of new concepts or theories, as well as “give experts in a domain the ability to solve problems quickly” (McCormick, 1997, p. 148). Concepts form the basis of conceptual knowledge, which is “formed in memory by the integrated storage of meaningful dimensions selected from known examples and the connecting of this entity in a given domain of information” (Tennyson & Cocchiarella, 1986, p. 41). Unlike declarative knowledge, conceptual knowledge requires understanding the operational structure of something and how it relates to associated concepts. A concept can be defined as “an abstract label that encompasses an array of diverse instances deemed to be related” (Sigel, 1983, p. 242). Similarly, Erickson (2002) offered that a concept is an organizing idea that is timeless, universal, abstract and broad, represented by

one or two words, and examples of which share common attributes. Conceptual knowledge can be “thought of as a connected web of knowledge, a network in which the linking relationships are as prominent as the discrete pieces of information” (Hiebert & Lefevre, 1986, p. 3-4).

Erickson (2002) argued that attempting to “teach in the 21<sup>st</sup> century without a conceptual schema for knowledge is like trying to build a house without a blueprint” (p. 7). Bransford and Donovan (2005) concurred, arguing that clarity of the core concepts of the discipline “is required if students are to grasp what the discipline – history, math, or science – is about” (p. 576). Teaching for conceptual understanding requires that the core concepts that organize the knowledge of experts also organize instruction. Donovan and Bransford (2005) concluded that this approach to teaching has two parts: “(1) factual knowledge (e.g., about characteristics of different species) must be placed in a conceptual framework (about adaptation) to be well understood; and (2) concepts are given meaning by multiple representations that are rich in factual detail” (p. 6).

According to Bransford, Brown, and Cocking (2000), in order to “develop competence in an area of inquiry, students must: (a) have a deep foundation of factual knowledge, (b) understand facts and ideas in the context of a conceptual framework, and (c) organize knowledge in ways that facilitate retrieval and application” (p. 16). They added that this “will require both a deepening of the information base and the development of a conceptual framework for that subject matter” (p. 17). In addition, conceptual frameworks allow for greater learning transfer because it allows students to apply what they have learned to new situations and learn related information more quickly. Tennyson and Cocchiarella (1986) outlined an instructional design approach to conceptual teaching. They viewed the process of teaching concepts as threefold: (a) establishing a connection between the to-be-learned concept and specific necessary knowledge, (b) improving the formation of the conceptual knowledge by elaborating further the schematic structure of relational concepts, and (c) improving development of procedural knowledge skills. This approach to instruction means there is “a need to establish criteria for delineating the content boundaries of a concept” (Sigel, 1983, p. 243).

### **Method**

This qualitative study was conducted by a team of three researchers with diverse experiences in secondary school engineering education. With qualitative research, it is important to reference the researchers’ backgrounds and relevant qualifications. The researchers’ backgrounds and experiences provide “lenses” through which the outcomes were generated and reflected upon (Malterud, 2001). Dr. Rodney L. Custer has been extensively involved in standards, curriculum, and professional development. His formal academic work includes an industrial engineering cognate in the PhD program and degrees in education, psychology and theology. He has served on several National Academy of Engineering studies focused on technological literacy and was a program officer at the National Science Foundation. Dr. Jenny L. Daugherty has served as a curriculum specialist on an engineering-oriented secondary level curriculum project, conducted several national teacher engineering-oriented workshops, and been involved in numerous funded projects focused on K-12 STEM education. With a firm grasp of the issues involved in secondary level engineering education, she also brings a broad liberal arts perspective with college degrees in History and Sociology. Joseph P. Meyer worked as a civil engineer before pursuing a master’s degree in science education and teaching secondary mathematics and science. With these experiences, he is familiar with the technical and

professional aspects of engineering as well as the institutional, social, and curricular challenges present when teaching secondary level mathematics and science students.

In addition to outlining the researchers' backgrounds, it is important in qualitative research to outline the evolution of the data collection process. The primary data collection methods for this study included: (a) an extant document review, and (b) focus groups; with the original plan to initiate data collection with the focus groups. However, it was decided that in order to best frame the focus group process, the researchers needed to engage in a thorough review of the literature that explored the philosophical underpinnings of engineering and technology. This review helped frame the focus group sessions and review of the remaining three sets of documents. Thus the extant document review evolved from the initial data collection plan. Ultimately, four sets of documents were included and underwent review for this study. In the order they were reviewed, these documents included: (a) engineering and technology philosophy writings, (b) curriculum materials focused on secondary level engineering, (c) curriculum standards documents developed for the STEM disciplines and relevant National Academy of Engineering reports, and (d) survey research studies relevant to K-12 engineering. The final phase of the process included a reaction panel of engineering and technology education experts who reviewed and discussed the study's methods and outcomes.

### *Extant Document Review*

The goal of the document review was to systematically identify and review key documents to identify core engineering concepts. The selection of documents for analysis varied depending on type. The philosophy literature was selected by one of the researchers whose doctoral dissertation included a thorough treatment of engineering and technology philosophy. Curriculum materials were drawn from those identified as appropriate for secondary level engineering education by Dr. Ken Welty (2009) as part of a commissioned study of K-12 engineering for the National Academy of Engineering and the National Research Council. Only those modules or units directly related to engineering were reviewed. The standards documents included in the study were those developed by the professional organizations representing the STEM disciplines. The research studies, largely consisting of modified Delphi and survey research, were identified through electronic database searches based on their research orientation and relevance for secondary level engineering.

The engineering and technology philosophy writings reviewed were *Engineering Philosophy* (Bucciarelli, 2003); *Thinking Through Technology: The Path Between Engineering and Philosophy* (Mitcham, 1999); *The Introspective Engineer* (Florman, 1996); *Engineering as Productive Activity* (Mitcham, 1991); *The Social Captivity of Engineering* (Goldman, 1991); *The Eco-philosophy Approach to Technological Research* (Skolimowski, 1991), *Deficiencies in Engineering Education* (Ropohl, 1991); *What Engineers Know and How They Know It* (Vincenti, 1990); *Ethics and Engineering* (Martin & Schinzinger, 1996); *Definition of the Engineering Method* (Koen, 2003); *Autonomous Technology and Do Artifacts Have Politics* (Winner, 1977); and *Technology as Knowledge* (Layton, 1974).

The curricula included for analysis were *A World in Motion* (SAE International); *Design and Discovery* (Intel Corporation); *Materials World*; *Engineering by Design*; *Engineering the Future*; *Exploring Design and Engineering*; *Ford Partnership for Advanced Students*; *INSPIRES*; *Project Lead the Way*; and *The Infinity Project*. The curriculum standards reviewed

for this study included: *Benchmarks for Science Literacy* (AAAS, 1993/2009), *Criteria for Accrediting Engineering Programs* (ABET, 2000), *National Science Education Standards*, (NRC, 1996), *Principles and Standards for School Mathematics* (NCTM, 2000), *Standards for Technological Literacy* (ITEA, 2000). In addition, the National Academy of Engineering's 2005 study *The Engineer of 2020* was also reviewed. The five survey research studies reviewed were: Childress and Rhodes (2008); Harris and Rogers (2008); Childress and Sanders (2007); Smith (2006); and Dearing and Daugherty (2004).

A standard process was developed and used to review each set of documents. Two of the three researchers reviewed each set of documents and identified “engineering themes” in the narrative. Engineering themes were those elements in the narrative that were described as important to engineering and applicable across various engineering disciplines. At this stage in the process, the decision was made to be inclusive, retaining themes that would later be analyzed and refined through a systematic, analytical procedure employed by the research team. Each of the reviewers recorded the theme, supporting narrative, and page number in a table. After the independent reviews were conducted, the results were compared and any differences were reconciled.

From this preliminary list of engineering themes, all three researchers independently identified what they considered to be core engineering concepts using a set of criteria defined through the literature. Specifically, each item was required to meet established definitions of engineering, concepts, and core. The definitions are as follows:

- Engineering: defined by the Accreditation Board for Engineering and Technology (ABET) as the knowledge of the mathematical and natural sciences, gained by study, experience, and practice, is applied with judgment to develop ways to use, economically, the materials and forces for the benefit of mankind (Gomez, Oakes, & Leone, 2006). The research team focused specifically on the study, expertise, and practice specific to engineering education and experience.
- Concepts: Abstract labels; organizing ideas; typically represented with one or two words; and take on meaning in the knowledge-rich contexts in which they are applied. (Erickson, 2002; Hiebert & Lefevre, 1986; Sigel, 1983; Tennyson & Cocchiarella, 1986). The team's deliberations concentrated on the robustness and complexity of ideas, where the ideas could be “unpacked” and where they extended well beyond procedural ideas.
- Core: The center of an object; a small group of indispensable things; and the most essential or most vital part of some idea or experience (Wordnet, 2009). In addition to being essential to engineering, the team's determinations of core hinged on their appropriateness to the secondary level.

To the extent possible, the review identified concepts distinct from the more “process-oriented skills” and “social/interpersonal dispositions” aspects of engineering. Following the independent ratings, the three listings were compared for continuity and subjected to a set of criteria used to meet the definition of a core engineering concept.

### *Focus Groups*

In addition to the thorough document review, the researchers conducted three focus group sessions with engineering educators and practicing engineers. The purpose of these sessions was closely aligned with the document-based review, where the goal was to capture the participants'



thinking about engineering concepts distinct from the process and interpersonal aspects of engineering. Several factors contributed to the importance of the focus group component of this study. First, very few, if any, of the documents reviewed for the study were specifically designed to identify engineering concepts. As a result, the review and synthesis process involved “teasing” concepts from materials developed for other purposes. The second reason for the focus groups was to probe the thinking of individuals with demonstrated ability to think broadly and conceptually about engineering practice and engineering education. In contrast to the more indirect approach inherent in the document review process, the focus groups provided a structured, direct approach to identifying concepts.

The focus groups were comprised of engineering education faculty and practicing engineers from selected departments of engineering and local engineering firms. A point person at each of the universities familiar with the issues involved with secondary level engineering education identified individuals to participate in the focus group sessions based on guidance from the research team. The goal of the selection criteria was to identify individuals with recognized interest in and expertise with the broader, conceptual aspects of engineering as well as an interest in secondary level education. The faculty selected to participate in the focus groups taught entry level, orientation types of engineering courses. These courses are designed to be more general and not focused on content specific to any one engineering discipline. Practicing engineers were selected based on their ability to think broadly about engineering education. One focus group session was conducted at Colorado State University and two at Virginia Tech University.

The focus group sessions were conducted concurrent with the analysis of the philosophy documents. The sessions were facilitated using an affinity group process technique, which consists of three steps. First, the participants were provided with an orientation to what is meant by engineering concepts as well as how these concepts are distinctly different from process and interpersonal skills. Each individual was then given five minutes to identify and write concepts onto sticky notes (one concept per card). The cards were placed onto a large wall for display and review. The group was led through a process of clustering the concepts into categories, which was followed by naming each category on a group consensus basis. As a group, the participants eliminated redundancies by placing duplicates on top of each other to retain frequencies. The group then classified concepts into three columns: (a) those core to engineering, (b) those very much on the fringe, and (c) those undecided or somewhere in the between core to or on the fringe of engineering.

### *Reaction Panel*

The culminating activity of the study consisted of a reaction process conducted by a panel of six engineering and technology education experts. Participants were selected based on their recognized ability to think conceptually, knowledge of secondary level education, and understanding of the engineering profession. The reaction panel was asked to reflect on and discuss the methods and outcomes of the review and synthesis activities. The panel was conducted using a two-part process designed to compare and contrast the outcomes of the study with the group’s own expertise and thinking. In the first part, participants were led through the same concept-identification process utilized in the three earlier focus group sessions. In addition to generating a body of concepts and framing the goals of the investigation, this beginning activity served to familiarize the participants with the process undertaken by the focus groups.

The second part of the activity led participants through a series of discussions designed to analyze the panel's concepts in light of the synthesized findings from the study.

### Findings

The study's findings are comprised of a synthesis of five major analyses including: (a) key history and philosophy of engineering and technology documents; (b) focus groups, (c) curriculum materials; (d) standards documents; and (e) research studies focused on identifying engineering and technological outcomes. The five analyses yielded an extensive listing of over 100 themes, judged by the research team to be pertinent to engineering. All three members of the research team independently applied the three criteria central to the analysis to each of the themes (i.e., core, engineering, and conceptual) across all of the five sets of materials. Subsequent to these individual analyses, the team met and engaged in extensive discussions to compare ratings and to achieve consensus on items judged to meet all three criteria. This process generated a listing of core engineering concepts for each of the five sets of materials. After consensus was achieved, a composite listing of concepts, across all five inputs, was compiled. Figure #1 depicts a set of thirteen concepts generated through this process, along with brief descriptions and an indication of whether the concept was represented in each of the five input sources. It should be noted that the descriptions are directly based on terminology used in documents throughout the analysis.

Table I

*Core Engineering Concepts and Presence in Data Sources*

Concept	Description	Curriculum	Philosophy	Standards	Focus Groups	Survey Studies
analysis	risk, cost/benefit, life-cycle, failure, mathematical, decision, functional, economic	•	•	•	•	•
constraints	criteria, specifications, limitations, requirements	•	•	•	•	•
design	iterative, technological, analysis based, experimental, ergonomic, universal	•	•	•	•	•
efficiency	key engineering goal, guiding principle	•	•	•	–	–
experimentation	testing, test development, trial and error	•	•	•	•	•
functionality	key engineering goal, usefulness, practicality	•	•	–	•	•
innovation	creativity, improvement, refinement, invention	•	•	•	•	•
modeling	mathematical, computer-based, sketching, technical drawing, physical	•	•	•	•	•
optimization	improvement, refinement, balancing, decision heuristics	•	•	•	•	•
prototyping	physical and process modeling and evaluation, preliminary	•	•	•	•	•

systems	input/output, process, feedback, component design and interaction, subsystems	•	•	•	•	•
trade-offs	conflicting constraints, negotiation, competing requirements or criteria	•	•	•	•	•
visualization	imagery, spatial and abstract representation, sketching	•	•	•	-	•

*Note.* • indicates concept present in data source, - indicates concept absent from data source

The listing presented in Figure #1 represents a distillation of a longer listing of over 100 themes. A substantial number of themes were deemed to have met the “core” and “engineering” criteria, but not the “conceptual” criterion. While these are important ideas, the goal of this study was to carefully identify ideas judged to be conceptually robust. Of those that met all three criteria, remarkable conceptual consistency was observed across the study’s five major inputs. Ten of the thirteen concepts were represented in all five inputs and two additional concepts were represented in four of the five inputs. Collectively, this represents strong cohesion across the materials reviewed. It is also clear that considerable conceptual overlap and interaction exists among the concepts. For example, many, if not most, of the concepts represent elements or aspects of the engineering design process. This conceptual overlap makes sense given the interconnected nature of engineering design. Also, functionality and efficiency are key engineering constraints.

It is important to note that while the central focus of the study was to identify a set of core engineering concepts appropriate for secondary level engineering, the research team was also interested in a larger set of issues and implications associated with the process. This type of reflective discussion is consistent with how themes, issues, and outcomes emerge from qualitative research and data analysis. In order to capture these ideas, the research team maintained a set of reflective notes throughout the review and synthesis process. In addition, the reaction panel reflected on these and other issues, helping to refine the thinking of the researchers. These have been compiled and will be presented as part of the following sections of this manuscript.

### **Discussion**

The review and synthesis process used for this study generated a set of core engineering concepts appropriate for secondary level engineering education. More broadly, and perhaps more importantly, it should be noted that the outcomes of the study consist of much more than a list of core engineering concepts. The process used to identify the concepts raised a number of difficult questions and important issues for secondary level engineering education. For example, the discussions around two “problematic” concepts are note-worthy as far as insight into the decision-making processes of the researchers and the challenges encountered in generating a list of engineering concepts. Other more encompassing issues continuously emerged throughout the study and were documented. These issues were grouped into the following categories and discussed below: (a) the development of an engineering ontology for the secondary level, (b) the social context of engineering, and (c) pedagogical implications related to teaching engineering concepts.

### *Problematic Concepts*

Two concepts emerged throughout the analysis that generated lively discussions as to their inclusion on the list: problem solving and experimentation. Problem-solving emerged as a substantial theme across the five data sets. This makes sense given the fundamental nature of engineering design. Activities ranging from the clarification of design parameters relative to (often competing) design constraints to problems associated with translating engineering theory into practical outcomes all involve solving problems. Thus, at a practical implementation level, a compelling case was made for including problem-solving as a fundamental engineering concept. At a conceptual level, several issues emerged. First, problem-solving, viewed generically, extends far beyond engineering and technological activity into all realms of human existence. For example, in the social sciences, problem solving applies to everything from community relations to personal mental health issues.

Custer (1995) addressed these distinctions classifying problem-solving into three major categories based on Newell and Simon's (1972) notion of problem space. These three problem spaces include personal/social, scientific, and technological. Across these problem spaces, problem solving requires more than a broad conceptual understanding of what problem solving is, including procedural and domain-specific knowledge. As Jonassen (2000) articulated, problem solving varies according to problem type, problem representation, and individual differences. In addition, problems vary by how well they are structured, their complexity and abstractness, and the context within which they reside. Specific to technological or engineering problems, the concept of problem solving can be seen to represent an overarching concept subsuming design, invention, trouble-shooting (Custer, 1995) thus confusing its conceptual distinctiveness to engineering. In the reverse, engineering design can be seen as representative of or a type of problem solving (Jonassen, 2000). Given these challenges and after discussion with the reaction panel, problem-solving was not included on the final list of engineering concepts. The importance of problem-solving to engineering practice and education, however, should not be ignored.

Experimentation emerged as a strong theme throughout the analysis of the documents and with the focus groups. However, as with the case of problem solving, issues were raised concerning its inclusion as a core engineering concept. First, the term "experimentation" is closely identified with science and the scientific method. Within a scientific context, experimentation connotes a specific methodology designed to establish and test hypotheses with a goal of theory development. Within an engineering context, it has more to do generally with informed and incremental trial and error activities involved in making a design work (e.g., extending human capabilities and meeting needs and wants). The argument could be made that the term experimentation is more appropriately associated with science than engineering. It is clear, however, that engineering is viewed as engineering science, particularly in academic circles, triggered in large part by increased federal funding for academic engineering research following World War II (Seely, 1993), and hastened by the launch of Sputnik in 1957. From this view, experimentation represents a formal analysis of applications of engineering theory. Although the term experimentation may connote other meanings beyond engineering, as evidenced by its emergence in all of the data inputs used in this study, within an engineering context it was deemed a core concept; thus included on the list.

### *Engineering Education Ontology*

As evidenced by the discussions of the two “problematic” concepts, the distinctions made to generate a list of core engineering concepts were important to the study. The overarching issues related to this endeavor are linked to the development of an engineering ontology for secondary level education. An ontology is a theory or a representative vocabulary about the objects, their properties, and relationships within a specific domain of knowledge. The identification of a representative vocabulary requires careful analysis and typically begins with clarifying the terminology for coherence and consistency. This involves devising a syntax for encoding knowledge in terms of concepts and relations. Ontologies form “the heart of any system of knowledge representation for that domain” (Chandrasekaran, Josephson, & Benjamins, 1999, p. 21). Although originally discussed in the field of philosophy, work has been done to establish ontologies in a variety of technical fields including artificial intelligence (i.e., Newell, 1982), information technology (i.e., Guarino & Poli, 1995), and industrial engineering (i.e., Borst & Akkermans, 1997). This study furthered this process for secondary engineering education by identifying core concepts and discussing some of their relationships to each other.

As with other domain-specific ontologies, the concepts used to define the field are not discrete or isolated from each other. All of the concepts on the list either directly relate to each other or overlap conceptually. For example, it was apparent throughout the analysis that engineering design is a central and dominant conceptual theme. In some of the documents reviewed, particularly the curriculum materials, the focus on engineering centered on engineering design. The steps of the engineering design process (e.g., problem formulation, brainstorming, prototyping) provided the framework for engineering. With other documents and in the focus groups, the discussion was somewhat broader, dealing with other aspects of engineering (e.g., functionality, efficiency, systems, and optimization). Although these aspects can also be considered to be subsumed by engineering design, they were presented as more robust concepts independent of the steps within the engineering design process, thus listed as separate concepts. However, design can be considered the primary engineering concept or even a threshold concept (Meyer & Land, 2006). Threshold concepts are distinguished from core concepts in that they are “akin to a portal, opening up a new and previously inaccessible way of thinking about something” (p. 3). Engineering design could provide the “portal” for all other engineering concepts and themes appropriate for the secondary school level.

Related to defining an engineering ontology, throughout the analysis, the research team struggled with the extent to which a conceptual base for engineering can be defined in terms of being uniquely engineering. More specifically, what concepts and knowledge, if any, can be said to be strictly distinct to engineering. The team concluded that this was problematic for two primary reasons. First, the engineering field is comprised of a spectrum of disciplines, each of which tends to draw on knowledge specific to each engineering discipline. For example, the knowledge base for nuclear engineering is distinct from that of civil engineering, with each composed of the knowledge necessary to conduct activities and analyses specific within each particular field. The question raised then was whether the disciplines share a common conceptual core that can be generalized across the disciplines. The second problem with conceptualizing an engineering ontology is that much of engineering is grounded in and interwoven with knowledge from other academic disciplines, particularly science and mathematics. In this regard, the field of engineering struggles with similar perceptions as technology; namely, that technological knowledge is essentially from the application of knowledge from other disciplines.

### *Social Context of Engineering*

The issue of engineering knowledge extends beyond ontology to issues related to “engineering practice” and “engineering dispositions.” This issue emerged particularly from the focus group discussions, where an attempt was made to draw distinctions between concepts that engineers primarily “know” and those they primarily “do” as professionals. These distinctions were difficult for the engineers to draw given the applied and socially grounded nature of engineering practice. Throughout the analysis of the documents, social issues continually emerged as important to engineering. Primary among these were ethics and interpersonal skills, such as communication and teamwork. This is not surprising given the emphasis on engineering ethics and interpersonal skills within postsecondary engineering. As Herkert (2000) pointed out, spurred in part by the social context and concerns over such things as the environment, and the standards promoted by the Accreditation Board for Engineering and Technology (ABET), *ABET Criteria 2000*, “engineering educators began to take seriously the challenge of educating professionals who are both technically competent and ethically sensitive” (p. 303).

Engineering ethics is a distinct type of ethics, in that it encompasses ethical decisions applied to specific practical problems within engineering (Bouville, 2008). There are many ethical dimensions of the professional responsibility of engineers including, public safety and welfare; integrity in the representation of data; and accountability to clients and customers (Herkert, 2000). While ethics and interpersonal skills did not meet the criteria for core engineering concepts established for this study, it is clear that engineering activity is consciously grounded within a larger system reflecting the values, needs, and impacts on societies and culture. Engineering and technology are inherently social constructs (Bijker, Hughes, & Pinch, 1989) and these contextual issues are important if core engineering concepts are to be formulated and understood in a meaningful way. The importance placed on ethics and interpersonal skills by postsecondary engineering should inform secondary level engineering education.

### *Pedagogical Implications*

Another important issue raised most directly by the reaction panel was the pedagogical implications of teaching the engineering concepts identified in this study. Many of the panelists questioned how these concepts could appropriately inform curriculum and instruction at the secondary level. Concerns were raised about the viability and wisdom of building units of instruction around the concepts in isolation of specific domain knowledge and abstract from specific contexts. As Donovan and Bransford (2005) indicated, concepts are only a piece of the puzzle. Concepts provide a framework for students to understand factual knowledge and use that understanding in different ways. Concepts do not stand alone but “take on meaning in the knowledge-rich contexts in which they are applied” (Donovan & Bransford, 2005, p. 6). Thus, the list of concepts generated through this study are not intended to encompass the entire domain of secondary level engineering or be implemented in isolation or in an abstract manner in the classroom.

However, just as concepts are not intended to be taught in isolation, procedural knowledge should not be taught abstracted from content or concepts. An understanding of process (i.e., the design process) requires the learning of content; each “piece of subject matter is a way of knowing, a way of representing, or a way of solving problems” (Costa & Lieberman, 1997, p. 14). Within a technological domain such as engineering, this view of learning requires that teachers identify the possible knowledge requirements of tasks, ascertain students’ relevant prior knowledge, and provide adequate support for conceptual development (McCormick, 1997). Activities such as design, modeling, and optimization “are all candidates for technological

procedural knowledge, and can be found across many technologies whatever their specific context” (McCormick, 1997, p. 144). However, the specific context is important in the development of technological knowledge as it is “dependent upon considerable domain knowledge” (McCormick, 1997, p. 146). The concepts generated in this study provide a conceptual base of understanding engineering that can transfer across contexts. However, the domain knowledge specific to a context is equally as important to understanding and reflecting upon the meaning of the concepts.

Related to these pedagogical implications, is the broader issue of the purpose of engineering at the secondary level. An often discussed issue by the team of researchers was to what end these concepts should inform instruction at the secondary level. At one extreme is pre-collegiate education designed for those preparing for engineering education at the post-secondary level. At the other extreme is a view that a general knowledge of engineering and how things are designed is appropriate and even necessary for all students as an orientation to living in a technologically rich culture. These different conceptualizations of pre-collegiate engineering raise questions about whether the concepts identified in the study are appropriate/important to engineering for both pre-engineering and general literacy purposes. Neither conceptualization was given precedence over the other in the analysis because the pursuit of “core” concepts was deemed appropriate for either a literacy or pathway approach. However, the pedagogical implications of implementing these concepts may differ according to the orientation toward either a general literacy approach or an approach that is intended to prepare students for postsecondary engineering education.

### **Recommendations**

Given the framework of an ontological approach for secondary level engineering education, it is important that these concepts be seen as the initial phase of research. As Chandrasekaran, Josephson, and Benjamins (1999) pointed out, constructing an ontology is an ongoing research enterprise. They recommended sharing the knowledge representation language generated through careful analysis with others who have similar needs for knowledge representation in that domain so as to eliminate the need for replication. This can then lead to building specific knowledge bases for specific situations (i.e., curriculum). It is recommended that this study be used to further that process. Specifically, the interrelationships between the concepts should be more fully explored. An excellent model to help guide this type of work is the *Atlas of Science Literacy* (AAAS, 2001).

In addition, the limitations of this study warrant further exploration. The research team focused on secondary level engineering education and selected documents reflective of that focus. An important issue that should be explored more fully is whether the concepts at the secondary level are applicable across the entire K-12 spectrum. If engineering is to take root in the K-12 landscape, this issue would need to be resolved. There are a variety of engineering-oriented projects focused on the lower grades (e.g., *Engineering is Elementary*, *Children Designing and Engineering*, and *Learning by Design*) that could help inform the process. In addition, focus groups with elementary and middle school teachers would help address the feasibility of these concepts at the lower grade levels.

### **Conclusion**

This study concentrated primarily on identifying a conceptual foundation for secondary level engineering education. It should be apparent that this represents a daunting task, triggering

a number of associated conceptual and practical issues. These issues have important implications for education if engineering is to be seriously considered as an integral part of the K-12 curriculum. These issues could significantly impact educational policy at the pre-collegiate level where the case remains to be made for including engineering content, as well as at the post-secondary level with a growing call for reform in engineering education. Additional areas that warrant further investigation include the possible need for K-12 engineering standards, curriculum, and teacher pre-service and professional development. The central premise of this study is that these issues are best addressed after the conceptual foundation has been carefully and thoughtfully developed.

### References

- Accreditation Board for Engineering and Technology, Inc. (ABET). (2000). *Criteria for accrediting engineering programs*, <http://www.abet.org/>.
- American Association for the Advancement of Science (AAAS). (1993/2009). *Benchmarks for science literacy*. Project 2061. New York: Oxford University Press.
- American Association for the Advancement of Science (AAAS). (2001). *Atlas of science literacy*. Project 2061. Washington, DC: American Association for the Advancement of Science and National Science Teachers Association.
- Antony, G. (1996). Active learning in a constructivist framework. *Educational Studies in Mathematics*, 31(4), 349-369.
- Aung, W., Kwasiborksi, V., & Soyster, A. L. (2007). A review of engineering education 1998-2007. Division of Engineering Education and Centers, Directorate for Engineering, National Science Foundation.
- Bijker, W., Hughes, T. P., & Pinch, T. (1989). *The social construction of technological systems*. Boston, MA: MIT Press.
- Borst, W. N., & Akkermans, J. M. (1997). Engineering ontologies. *International Journal of Human-Computer Studies*, 46(2/3), 98-114.
- Bouville, M. (2008). On using ethical theories to teach engineering ethics. *Science & Engineering Ethics*, 14, 111-120.
- Bransford, J. D., Brown, A. L., & Cocking, R. R. (Eds.). (2000). *How people learn: Brain, mind, experience, and school*. Washington, DC: National Academy Press.
- Bransford, J. D., & Donovan, M. S. (2005). Scientific inquiry and how people learn. In M. S. Donovan, & J. D. Bransford (Eds.). *How Students Learn: History, Mathematics, and Science in the Classroom* (pp. 397-419). Washington, DC: National Academies Press.
- Bucciarelli, L. L. (2003). *Engineering philosophy*. Delft University Press: The Netherlands.
- Chandrasekaran, B., Josephson, J. R. & Benjamins, V. R. (1999). What are ontologies, and why do we need them? *IEEE Intelligent Systems*, 14(1), 20-26.
- Childress, V., & Rhodes, C. (2008). Engineering student outcomes for grades 9-12. *The Technology Teacher*, 5(7), 5-12.
- Childress, V., & Sanders, M. (2007). Core engineering concepts foundational for the study of technology in grades 6-12. In R. Custer (Ed.). *Professional development for engineering and technology: A national symposium*, February 2007. Retrieved September 03, 2008, <http://www.conferences.ilstu.edu/NSA/homepage.html>.
- Costa, A. L., & Liebmann, R. M. (1997). Toward renaissance curriculum: An idea whose time has come. In A. L. Costa, & R. M. Liebmann. (Eds.). *Envisioning process as content: Toward a renaissance curriculum* (pp. 1 – 20). Thousand Oaks, CA: Corwin.



- Custer, R. L. (1995). Examining the dimensions of technology. *International Journal of Technology and Design Education*, 5(5), 219-244.
- Daugherty, J. L. (2008). *Engineering-oriented professional development for secondary level teachers: A multiple case study analysis*. Unpublished doctoral dissertation. University of Illinois, Urbana-Champaign.
- Dearing, B. M., & Daugherty, M. K. (2004). Delivering engineering content in technology education. *The Technology Teacher*, 64(3), 8-11.
- Desimone, L. M., Porter, A. C., Garet, M. S., Yoon, K. S., & Birman, B. F. (2002). Effects of professional development on teachers' instruction: Results from a three-year longitudinal study. *Educational Evaluation and Policy Analysis*, 24(2), 81-112.
- Donovan, M. S., & Bransford, J. D. (2005). Introduction. In M. S. Donovan, & J. D. Bransford (Eds.). *How students learn: History, mathematics, and science in the classroom* (pp. 1-28). Washington, DC: National Academies Press.
- Eisenhart, M., Borko, H., Underhill, R., Brown, C., Jones, D., & Agard, P. (1993). Conceptual knowledge falls through the cracks: Complexities of learning to teach mathematics for understanding. *Journal for Research in Mathematics Education*, 24(1), 8-40.
- Erekson, T. L., & Custer, R. L. (2008). Conceptual foundations: Engineering and technology education. In R. L. Custer, & T. L. Erekson. *Engineering and technology education*. 57<sup>th</sup> Yearbook, Council on Technology Teacher Education (pp. 1-12). Woodland Hills, CA: Glencoe.
- Erickson, H. L. (2002). *Concept-based curriculum and instruction: Teaching beyond the facts*. Thousand Oaks, CA: Corwin.
- Florman, S. (1996). *The introspective engineer*. New York: St Martin's Press.
- Goldman, S. L. (1991). The social captivity of engineering. In P. T. Durbin (Ed.), *Critical perspectives on non academic Science and Engineering*, Lehigh University Press, Bethlehem, PA.
- Gomez, A. G., Oakes, W. C., & Leone, L. L. (2006). *Engineering your future: A project-based introduction to engineering*. 2<sup>nd</sup> ed. Wildwood, MO: Great Lakes Press.
- Guarino, N., & Poli, R. (1995). The role of ontology in the information technology. *International Journal of Human-Computer Studies*, 43(5/6), 623-965.
- Guskey, T. (2003). What makes professional development effective? *Phi Delta Kappan* 84, 748-750.
- Harris, K. S., & Rogers, G. E. (2008). Secondary engineering competencies: A Delphi study of engineering faculty. *Journal of Industrial Teacher Education*, 45(1), 5-25.
- Herkert, J. R. (2000). Engineering ethics education in the USA: Content, pedagogy, and curriculum. *European Journal of Engineering Education*, 25(4), 303-313.
- Hiebert, J., & Lefevre, P. (1986). Conceptual and procedural knowledge in mathematics: An introductory analysis. In J. Hiebert (Ed.). *Conceptual and procedural knowledge: The case of mathematics* (pp. 1-27). Hillsdale, NJ: Lawrence Erlbaum.
- Hill, A. M., & Anning, A. (2001). Primary teachers' and students' understanding of school situated design in Canada and England. *Research in Science Education*, 31(1), 117-135.
- International Technology Education Association (ITEA). (2000). *Standards for technological literacy: Content for the study of technology*. Reston, VA
- Jonassen, D. H. (2000). Toward a design theory of problem solving. *Educational Technology Research and Development*, 48(4), 63-85.

- Koen, B. V. (2003). *Discussion of the method: Conducting the engineer's approach to problem solving*. New York, NY: Oxford University Press.
- Layton, E. T. (1974). Technology as knowledge. *Technology and Culture*, 15(1), 31-41.
- Lewis, T. (2005). Coming to terms with engineering design as content. *Journal of Technology Education*, 16(2), 37-54.
- Lewis, T., Petrina, S., & Hill, A. M. (1998). Problem posing: Adding a creative increment to technological problem solving. *Journal of Industrial Teacher Education*, 36(1), 5-35.
- Malterud, K. (2001). Qualitative research: Standards, challenges, and guidelines. *The Lancet*, 358, 483-488.
- Martin, M.W. & Schinzinger, R. (1996), *Ethics in engineering*. 3rd ed. New York: McGraw-Hill.
- Mawson, B. (2003). Beyond 'The Design Process': An Alternative pedagogy for technology education. *International Journal of Design Education*, 13(2), 117-128.
- McCormick, R. (1997). Conceptual and procedural knowledge. *International Journal of Technology and Design Education*, 7, 141-159.
- Meyer, J. H. F. & Land, R. (2006). Threshold concepts and troublesome knowledge: Linkages to ways of thinking and practising within the disciplines. In J. H. F. Meyer & R. Land, (Eds.). *Overcoming barriers to student understanding: Threshold concepts and troublesome knowledge* (pp. 3-18). London: Routledge Falmer.
- Mitcham, C. (1991). Engineering as productive activity: Philosophical remarks. In P. T. Durbin (Ed.). *Critical perspectives on nonacademic science and engineering. Research in Technology Studies*, Vol. 4. London and Toronto: Associated University Press.
- Mitcham, C. (1999), *Thinking through technology: The path between engineering and philosophy*. Chicago: University of Chicago Press.
- National Academy of Engineering (NAE). (2005). *The engineer of 2020: Adapting engineering education to the new century*. Washington, DC: National Academy Press.
- National Council Teachers of Mathematics (NCTM). (2000). *Principles and standards for school mathematics*. Reston, VA: NCTM.
- National Research Council (NRC). (1996) *National science education standards*, Washington DC: National Academy Press.
- Newell, A. (1982). The knowledge level. *Artificial Intelligence*, 18, 87-127.
- Newell, A., & Simon, H. (1972). *Human problem solving*. Englewood Cliffs, NJ: Prentice-Hall.
- Ropohl, G. (1991). *Deficiencies in engineering education*. In P. T. Durbin (Ed.). *Critical Perspectives on Nonacademic Science and Engineering. Research in Technology Studies*, Vol. 4. London and Toronto: Associated University Press.
- Rittle-Johnson, B., & Alibali, M. W. (1999). Conceptual and procedural knowledge of mathematics: Does one lead to the other? *Journal of Educational Psychology*, 91(1), 175-189.
- Rittle-Johnson, B., Siegler, R. S., & Alibali, M. W. (2001). Developing conceptual understanding and procedural skill in mathematics: An iterative process. *Journal of Educational Psychology*, 93(2), 346-362.
- Seely, B. E. (1993). Research, Engineering, and Science in American Engineering Colleges: 1900-1960. *Technology and Culture*, 34(2), 344-386.
- Sigel, I. E. (1983). Is the concept of the concept still elusive or what do we know about concept development? In E. K. Scholnick (Ed.). *New trends in conceptual representation: Challenges to Piaget's theory?* Hillsdale, NJ: Lawrence Erlbaum.

- Skolimowski, H. (1991). The eco-philosophy approach to technological research. In P. T. Durbin (Ed.). *Critical Perspectives on Nonacademic Science and Engineering. Research in Technology Studies*, Vol. 4. London and Toronto: Associated University Press.
- Smith, P. C. (2006). *Essential aspects and related academic concepts of an engineering design curriculum in secondary technology education*. Unpublished doctoral dissertation. University of Georgia, Urbana-Champaign.
- Supovitz, J., & Turner, H. (2000). The effects of professional development on science teaching practices and classroom culture. *Journal of Research in Science Teaching*, 37(9), 963-980.
- Tennyson, R. D., & Cocchiarella, M. J. (1986). An empirically based instructional design theory for teaching concepts. *Review of Educational Research*, 56(1), 40-71.
- Vincenti, W. G. (1990). *What engineers know and how they know it: Analytical studies from aeronautical history*. Baltimore, MD: Johns Hopkins University Press.
- Welch, M. (1999). Analyzing the tacit strategies of novice designers. *Research in Science & Technological Education*, 17(1), 19-34.
- Welty, K. (2009). Analysis of K-12 engineering education curricula. Work commissioned by the National Academy of Engineering/National Research. Council Committee on K-12 Engineering Education. Unpublished.
- Wicklein, R. C. (2006). Five good reasons for engineering design as the focus for technology education. *The Technology Teacher*, 65(7), 25-29.
- Williams, P. J. (2000). Design: The only methodology of technology?" *Journal of Technology Education*, 11(2), 48-60.
- Winner, L. (1977). *Autonomous technology: Technics-out-of-control as a theme in political thought*. M.I.T. Press, Cambridge, MA.
- Wordnet. Definitions of core on the web, Retrieved March 14, 2009, <http://wordnet.princeton.edu/perl/webwn>.